Seal test	Closing off the PRACLAY gallery	
Type of test: Hydro-mechanical behaviour of bentonite	**Collaborating partners:** Smet Tunnelling SECO Tractebel Engineering	**Period:** 2010 - ongoing

BACKGROUND

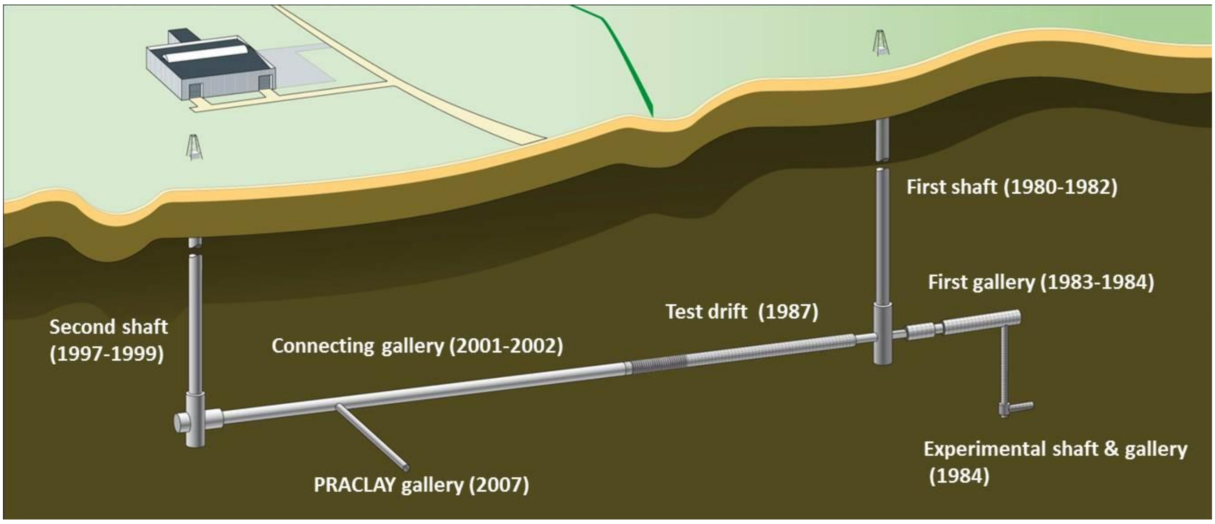


Figure 1 - Layout of the construction of the HADES underground research laboratory

In 2007, the 45 m long PRACLAY gallery was constructed in the HADES URL to host the large-scale PRACLAY Heater test (Figure 1). With this test, scientists want to study the impact of heat, produced by high-level radioactive waste, on the thermo-hydro-mechanical (THM) behaviour of the Boom Clay in conditions that are representative of an actual waste repository. The goal is to confirm on a large scale and refine existing knowledge from past small-scale heating experiments, performed both in HADES and in surface laboratories.

The PRACLAY Heater test was conceived to be conducted under a well-controlled and reasonably conservative combination of thermal, hydraulic and mechanical boundary conditions. This implies, among other requirements, quasi-undrained conditions. These conditions are achieved by introducing water-saturated backfill sand into the heated part of the gallery and installing a hydraulic seal at the intersection between the heated and the non-heated parts of the gallery (Figure 2). The **PRACLAY Seal test** is focusing on the design, installation and functioning of this seal.

Together, the construction of the gallery, the Seal test and the Heater test make up the **PRACLAY In-Situ Experiment**.

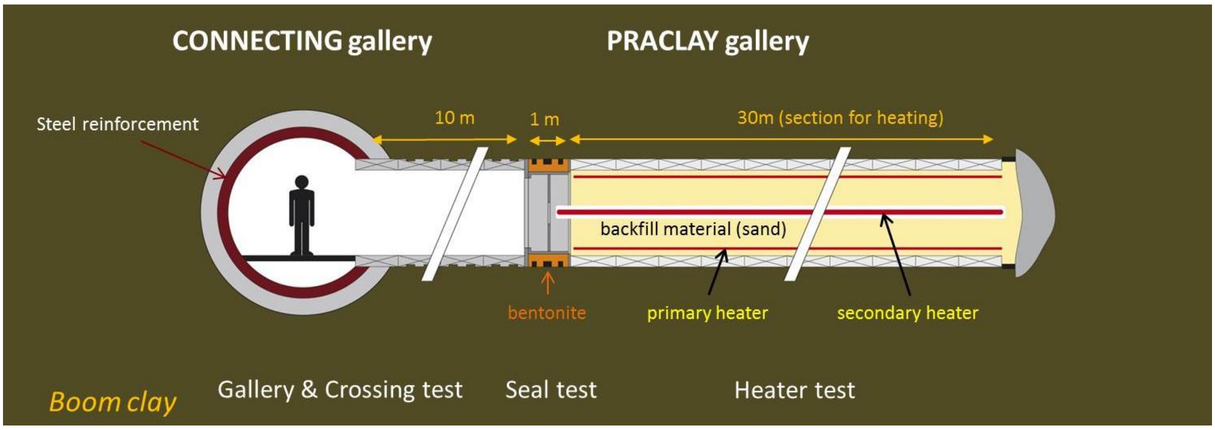


Figure 2 - The set-up of the PRACLAY In-Situ Experiment

OBJECTIVES

Heating under undrained boundary condition implies that a higher pore water pressure (PWP) at the interface between the concrete gallery lining and the clay is expected. This expected high PWP is achieved indirectly by introducing the water-saturated backfill sand into the heated part of the gallery: upon heating, a homogeneous high PWP is generated in this saturated backfill material due to its high thermal dilation properties. However, this high PWP has to be maintained. This is the main purpose of the seal: it has to hydraulically cut off the heated part of the PRACLAY gallery and surrounding clay from the non-heated part of the gallery and thus maintain the high pressure inside the heated section of the gallery.

The seal consists of a steel cylinder, surrounded by a ring of bentonite. Bentonite was used as a sealing material because of its intrinsically low permeability (when compacted to a suitable dry density) and its swelling capacity upon hydration by Boom Clay water, which helps to seal the excavation-induced zone around the seal. In this way, an almost impermeable zone is created at the intersection between the two parts of the gallery, helping to keep the pressure high inside the heated part of the PRACLAY gallery and consequently providing the quasi-undrained hydraulic boundary conditions for the PRACLAY Heater test (Figure 3).

Such an undrained boundary is chosen to achieve the conservative conditions that are reasonably achievable during the Heater test.

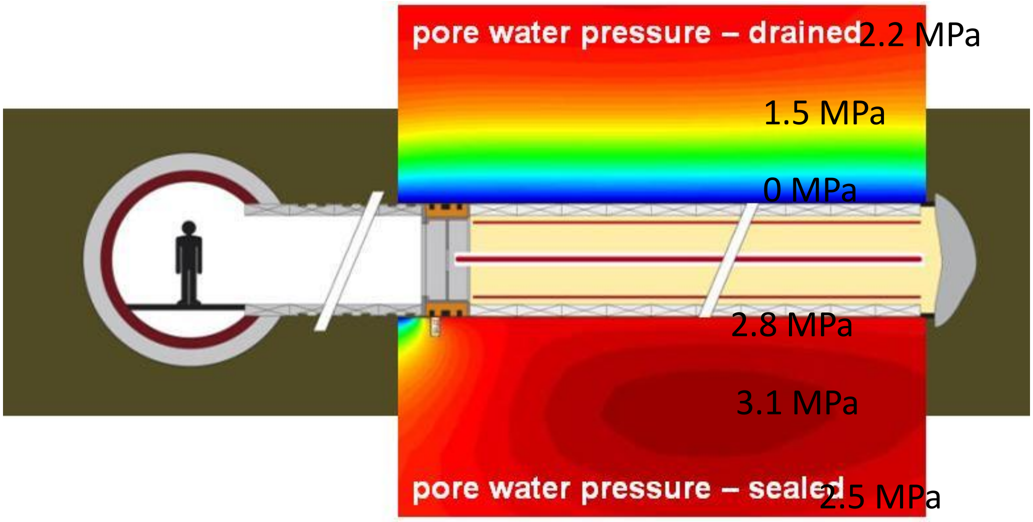


Figure 3 - Modelled pore water pressures in the clay around the Heater test, with a seal (undrained conditions) and without a seal (drained conditions)

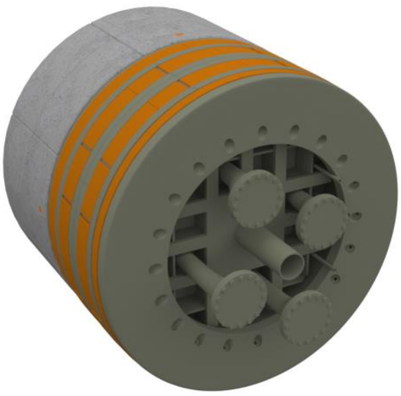
Together with the design and installation of the seal, studying the swelling behaviour of the bentonite ring since its installation are the main objectives of the **PRACLAY Seal test**.

The hydraulic seal is purpose-built for the PRACLAY Heater test and is not representative of seals in a real repository. However, the Seal test is a unique opportunity to gather additional information on the in-situ behaviour of bentonite-based repository structures and thus for studying the possibility of closing off galleries.

Finally, the hydraulic seal has to allow watertight feed-through of the instrumentation cables placed in the heated part of the PRACLAY gallery and watertight feed-through of the heater cables.

DESIGN and INSTALLATION of the seal

The seal consists of a stainless steel structure and an annular ring of compacted bentonite placed against the clay (Figure 4). The steel cylinder physically closes off the gallery. Bentonite was chosen as a sealing material because of its intrinsically low permeability (when compacted to a suitable dry density) and its swelling capacity upon hydration by Boom Clay water.



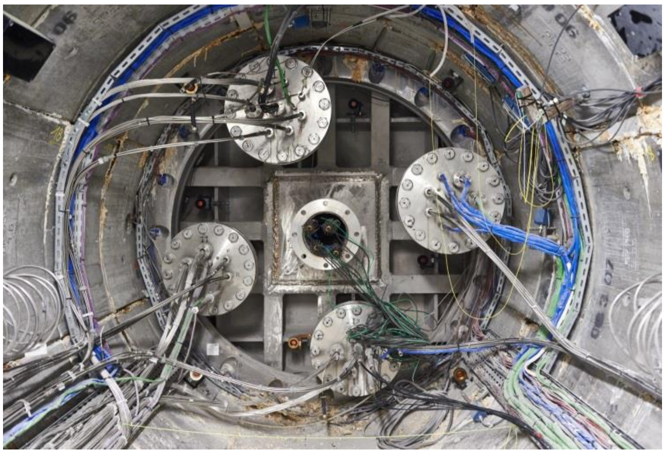


Figure 4 - 3D view of the seal with a central steel cylinder and an annular ring of bentonite (orange) against the clay (left) and front view of the seal from the non-heated part of the PRACLAY gallery (right)

The seal is installed 10 m from the Connecting gallery to limit the mutual interactions between the Heater test and the Connecting gallery. Scoping calculations indicate that a seal length of 1 m is sufficiently effective and that no significant gain was derived by further increasing its length. A bentonite-based hydraulic seal was chosen instead of, for example, a technical seal consisting of inflatable packers, as bentonite is generally considered to be a potentially suitable material for seals in repository designs for the disposal of radioactive waste. Although the design of the seal is primarily driven by the requirements of the Heater test and does not mimic the design of a repository seal, it can provide lessons on the feasibility of installing such a seal and on the behaviour of the bentonite.

The bentonite has to meet the following specifications:

- its swelling pressure (this is the pressure the bentonite exerts on the clay when the bentonite is completely hydrated) is larger than 2.5 MPa to avoid the creation of negative effective stresses around the hydraulic seal during the Heater test (the maximum pore water pressures in the Boom Clay around the hydraulic seal during the Heater test are estimated at 2.5 MPa);

- its maximum swelling pressure is 6 MPa to avoid fracturing the clay and not jeopardising the integrity of the stainless steel structure of the hydraulic seal;

- its hydraulic conductivity at saturated state is as low as possible (at least lower than the conductivity of undisturbed Boom Clay (≈ 10^{-12} m/s) and preferably one order of magnitude lower).

It was decided to use MX80 bentonite compacted into blocks. Relevant experience with this type of bentonite has been gained from its use in other experiments in underground research facilities (Mont Terri, Bure, ASPO and AECL's URL) and in the laboratory (by CEA, CIEMAT, CERMES and SKB). Furthermore, it is an Na-bentonite, which makes it chemically compatible with Boom Clay water. The initial dry density of the bentonite (1.8 t/m³), which affects its swelling pressure and saturated permeability, was determined by scoping calculations, taking into account the interaction between bentonite and Boom Clay.

The bentonite is naturally hydrated by pore water coming from the Boom Clay, and artificially by water injected through filters at the outside of the cylinder of the seal.

Instrumentation was placed in the bentonite blocks to gain information on the bentonite hydration and to be able to evaluate the performance of the hydraulic seal (Figure 5).

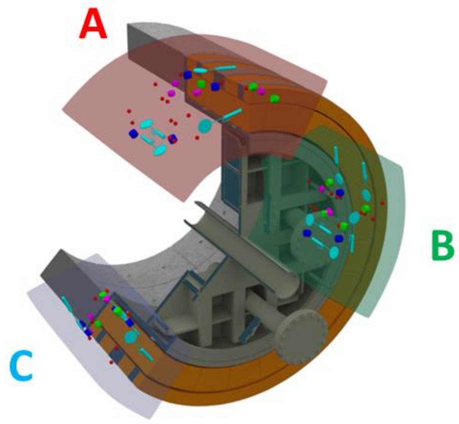


Figure 5 - Various instruments inside the bentonite, grouped into sections A, B and C

TIMING

The double layer of bentonite blocks and incorporated sensors for monitoring bentonite behaviour were installed between 13 January 2010 and 11 February 2010, followed by the installation of the stainless steel structure. As a consequence of direct contact between the Boom Clay and the bentonite ring, the natural hydration of the latter began immediately. When the stainless steel cylinder structure was installed, artificial hydration by water injection was started in April 2010.

After installation of the heating system and backfilling of the gallery with sand, the stainless steel structure was sealed on 13 October 2011 by welding a closing plate in position.

The PRACLAY Heater test started on 3 November 2014 after a detailed analysis and evaluation of the status and performance of the seal.

RESULTS

Figure 6 shows **the radial pressure at the bentonite/Boom Clay interface** in sections A and B of the seal. This pressure results from the equilibrium between the radial pressure exerted by the Boom Clay and the swelling pressure of the bentonite ring. It is observed that the pressure immediately started to increase upon contact with the saturated Boom Clay. The combination of the swelling pressure and the radial pressure generated a continuous increase in pressure with time. At the end of 2013, a series of characterisation tests took place and it was concluded that the pressure required to start the Heater test had been reached. The Heater test has caused a general increase in pressure since the start of the heating phase. Since the target temperature of 80°C was reached, the pressure has continued to increase, but at a slower rate.

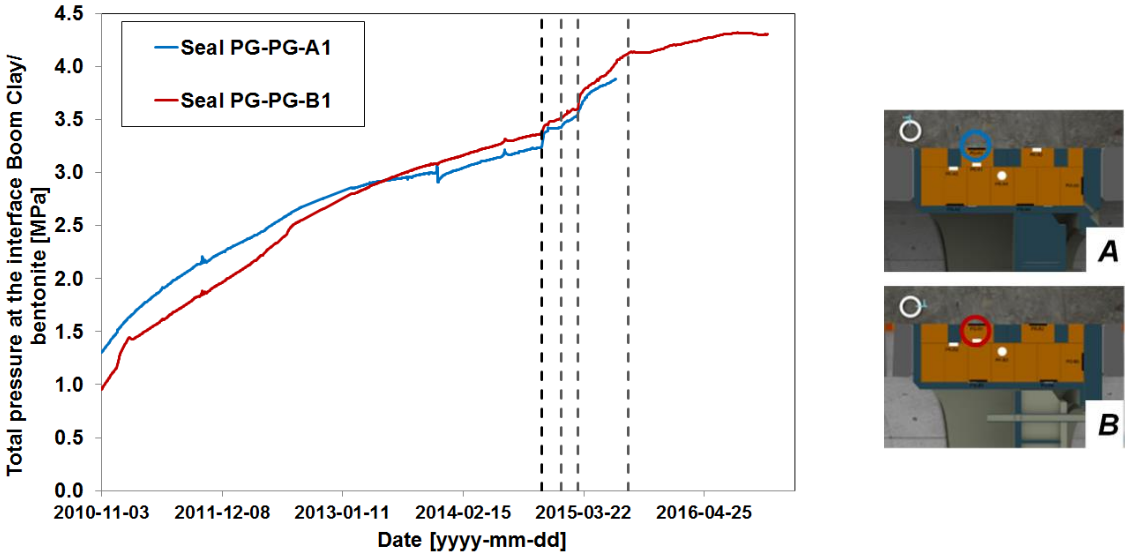


Figure 6 - Radial pressure measured at the Boom Clay/bentonite interface sidewall, for sections A and B. The dotted lines mark the phases of the heater experiment.

The pore water pressure is also monitored at the bentonite/Boom Clay interface, as can be seen in Figure 7 where a general increase in PWP with heating is observed. In addition to the PWP at the interface between both clays, the PWP inside the heated part of the PRACLAY gallery is also shown.

The measurements at different locations of the seal clearly show that the seal performs well as a hydraulic cut-off, maintaining a high PWP inside the gallery. Indeed, a high PWP gradient over the seal length is observed. More specifically, a pressure difference of approximately 1.3 MPa is observed between the heated part and the pressure sensor close to the non-heated part (*Seal PP-A3*). The PWP around the top of the seal, in section A, is shown in Figure 8. Between the heated (*Ring 21 S8*) and the non-heated part (*Ring 20 S8*) of the gallery, a difference of 2 MPa exists. This once again confirms that the seal is fulfilling its role as a hydraulic cut-off between the two different parts of the experiment.

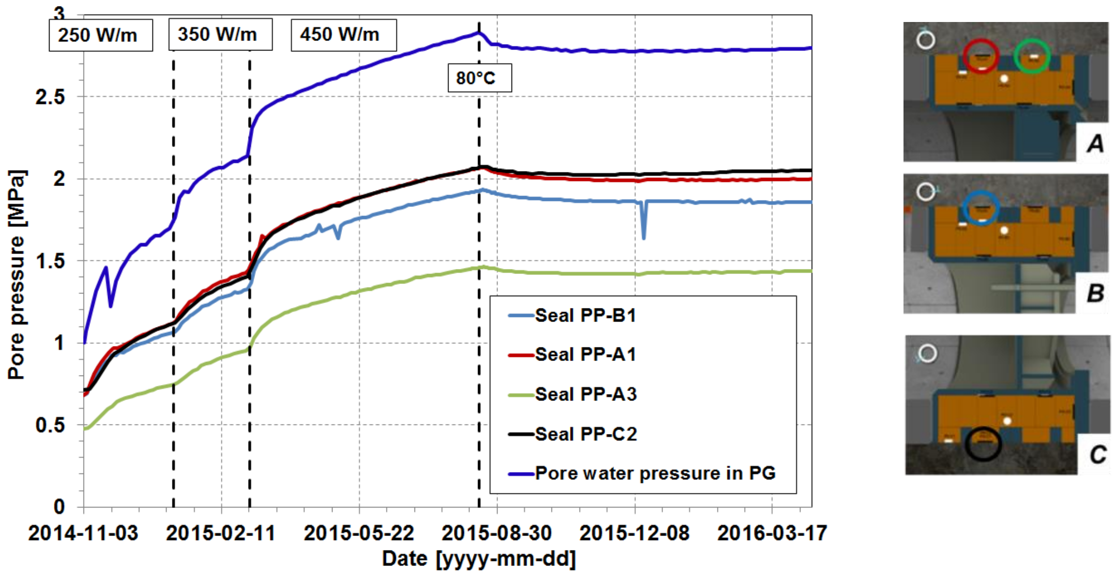


Figure 7 - Evolution of the pore water pressure at the Boom Clay/bentonite interface

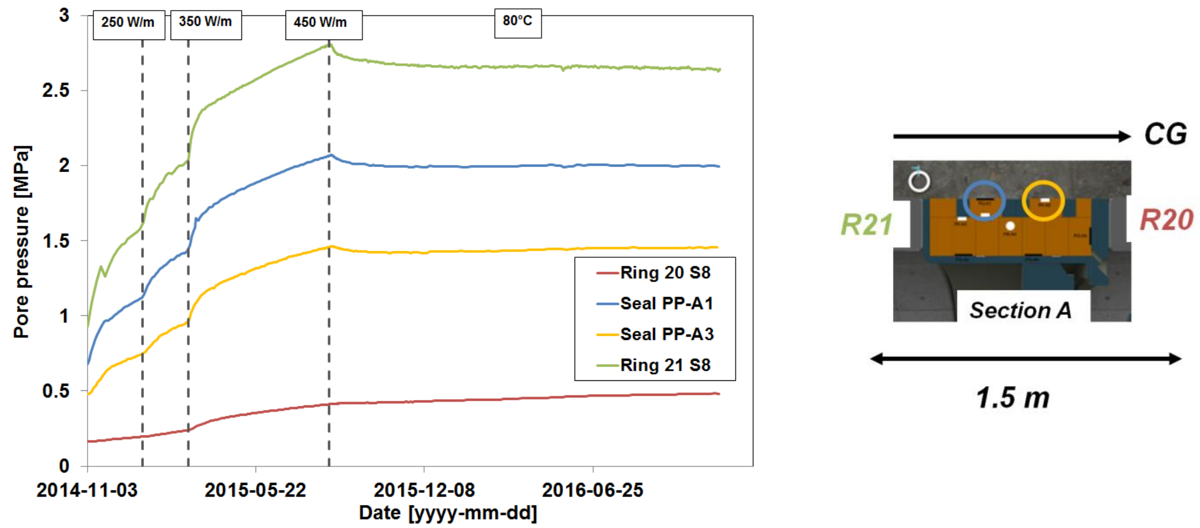


Figure 8 - Evolution of the pore water pressure around section A at the top of the seal

CONCLUSION

To obtain the required quasi-undrained hydraulic boundary conditions for the Heater test, a steel structure was installed, surrounded by a bentonite ring in direct contact with the Boom Clay. The results show that the seal is very effective in creating quasi-undrained hydraulic boundary conditions and helps to keep the pressure high inside the heated part of the experiment.

After the installation of the seal in 2010, swelling of the bentonite began due to artificial (injection) and natural (Boom Clay) hydration. This swelling created the minimal pressure conditions to start the Heater test in November 2014.

Since the target temperature of 80°C has been reached, the pore water pressure inside the PRACLAY gallery has stabilised at 2.7 MPa. The seal structure (steel cylinder and bentonite ring) closes off the gallery as intended and maintains the pressure high inside the heated section of the gallery. The high pore water pressure gradient over the seal (from non-heated to heated section) indicates that the seal is fulfilling its role in creating quasi-undrained hydraulic boundary conditions for the Heater test.

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